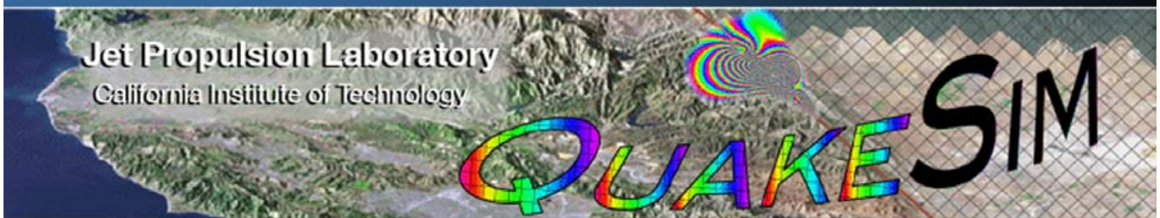
2005 Final Project Report



Numerical Simulations For Active Tectonic Processes: Increasing Interoperability And Performance

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2005 Final Report Completed

Numerical Simulations For Active Tectonic Processes: Increasing Interoperability And Performance

The QuakeSim Project

JPL Task Order: 10650

Milestone D – Administration ***due date: 11/30/04***

Final Report Delivered.

Executive Summary

Quakesim is a solid earth science framework for creating a better understanding of active tectonic and earthquake processes.

QuakeSim is a fully interoperable system for studying active tectonics and earthquakes. We have developed simulation and analysis tools to study the physics of earthquakes using state-of-the-art modeling, data manipulation, and pattern recognition technologies. We have developed clearly defined accessible data formats and code protocols as inputs to the simulations. These codes have been adapted to high-performance computers because the solid earth system is so complex and nonlinear. These tools have now made it possible to construct the more complex models and simulations necessary to develop hazard assessment systems critical for reducing future losses from major earthquakes.

We have completed delivery of a web-services problem-solving environment that links together diverse earthquake science applications on distributed computers. This portal environment has expanded to include many more applications and tools – such as the major simulation tools, data inverse code, pattern recognition, database access, and visualization code.

Particularly notable was the portal integration and use of the Pattern Informatics (PI) code that has successfully been used to forecast California seismic hotspot activity with an 11 km resolution. Of the most recent 18 “significant” earthquakes in California, 16 occurred within the forecast hotspots (see our scorecard at http://quakesim.jpl.nasa.gov/scorecard.html). We have submitted a paper to *Seimological Research Letters* with a 5-year forecast [see J.R. Holliday, C.C. Chen, K.F. Tiampo, J.B. Rundle and D.L. Turcotte, A RELM earthquake forecast based on Pattern Informatics, Seism. Res. Lett., in review (2005)]. After its integration into the QuakeSim portal, the PI code was used to forecast earthquakes in other regions of the world and to determine its sensitivity and range of application.

The team has also completed the high end computing implementation of three major simulation tools: PARK, GeoFEST and Virtual California and then delivered the QuakeSim portal system to our customers with 13 incorporated applications.

We achieved significant performance improvements to the simulation codes in this final year of the project. The capabilities of the PARK code have increased from 15,000 fault elements and 500 time steps in just under eight hours (one processor) to 400,000 fault elements and 50,000 time steps in under 35 hours on 512 processors. This was demonstrated on the JPL Dell Linux cluster. Integration with the parallel fast multipole method has resulted in a one hundredfold performance improvement in solving problems of this size, and has enabled simulations with much higher resolution than previously possible.

The GeoFEST code improvement effort has had similar success. We have demonstrated an improvement in capability from solving a 55,000 finite element problem in just under fourteen hours (one processor) to 16 million elements in 2.8 hours for the same number of time steps (490 processors on the Cosmos computer at JPL). Using parallel processors to adaptively refine an initial mesh (using the Pyramid library developed by the Computational Technologies (CT) project), enables the use of larger, more accurate meshes than those that could be generated on desktop machines. GeoFEST has been downloaded by 80 customers and been ported to ten different parallel machines, including Dell, SGI and Apple.

GeoFEST has been downloaded by more than 80 customers, including researchers from Stanford, MIT, Caltech, Harvard, USGS, Los Alamos National Laboratory, University of Texas, University of Illinois at Urbana-Champagne, MIT, West Virginia University, Murray State University, University of Memphis, Oregon State University, San Diego State University, USC, Michigan Tech University, Woods Hole Oceanographic Institution (WHOI), University of Miami, University of Colorado at Boulder, Columbia University, University of Arkansas, and the Rensselaer Polytechnic Institute.

Virtual California has met its code improvement goal of a speed up of M/2 on a set of partitions up to 256 processors, where M is the number of processors in each partition. Virtual California simulations form the basis of a forecast of the next great San Francisco Earthquake; this forecast is currently in press at the *Proceedings of the National Academy of Science* [Rundle, J.B., PB Rundle, A Donnellan, D Turcotte, R Shcherbakov, P Li, BD Malamud, LB Grant, GC Fox, D McLeod, G Yakovlev, J Parker, W Klein, KF Tiampo, A simulation-based approach to forecasting the next great San Francisco earthquake, Proc. Nat. Acad. Sci., 102: 15363-15367 (2005) ; published online before print October 11 2005, 10.1073/pnas.0507528102].

The team has used a number of forums to inform the geophysics and information systems community of QuakeSim's progress. In addition to the 53 peer-reviewed publications, the team has written 29 other articles, abstracts and posters. Another avenue of QuakeSim dissemination includes QuakeSim/SERVOGrid introductory tutorials at the 4th ACES (APEC Cooperation for Earthquake Simulation) workshop in Beijing, China, July 2004 and at the 2004 SCEC Fault Systems Working Group workshop at Los Alamos. Numerous media appearances by PI Andrea Donnellan and Co-I John Rundle have helped put a public face to the QuakeSim work.

QuakeSim has seven New Technology Reports and four NASA Space Act Awards.

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Objective

Project Objective

The full objective over this three-year program is to produce a system to fully model earthquake-related data. Components of this system include:

- A database system for handling both real and simulated data
- Fully three-dimensional finite element code (FEM) with an adaptive mesh generator capable of running on workstations and supercomputers for carrying out earthquake simulations

- Inversion algorithms and assimilation codes for constraining the models and simulations with data
- A collaborative portal (object broker) for allowing seamless communication between codes, reference models, and data
- Visualization codes for interpretation of data and models
- Pattern recognizers capable of running on workstations and supercomputers for analyzing data and simulations

In order to develop a solid Earth science framework for understanding and studying of active tectonic and earthquake processes, this task develops simulation and analysis tools to study the physics of earthquakes using state-of-the-art modeling, data manipulation, and pattern recognition technologies. We develop clearly defined accessible data formats and code protocols as inputs to the simulations. These are adapted to high-performance computers because the solid Earth system is extremely complex and nonlinear resulting in computationally intensive problems with millions of unknowns. With these tools it will be possible to construct the more complex models and simulations necessary to develop hazard assessment systems critical for reducing future losses from major earthquakes.

Project details and documentation are available at the QuakeSim main web page at http://quakesim.jpl.nasa.gov.

Final Year Objectives

Our objectives in the final year included integrating all target applications into the portal, establishing the parallel scalability of the major simulation tools, and delivering the documented system.

The QuakeSim "portal" objective was to complete an interoperable framework for linking processes on diverse remote host machines. This system implementation was successfully completed and documented in Milestone J *Interoperability Prototype* at http://quakesim.jpl.nasa.gov/milestones.html.

QuakeSim developed three high-end computing simulation tools: GeoFEST, PARK and Virtual California. The final year's "code improvement" objective was to further optimize these codes and make their documented source code publicly available via the Web. These code improvements were achieved and documented in Milestone G *Second Code Improvement* at http://quakesim.jpl.nasa.gov/milestones.html. The source code for these three tools is now accessible via this website http://quakesim/download.html.

The last project objective was to deliver the system to the customer. We demonstrated the integration of one external user application into the framework using the GRID framework wizards. We issued a testable 5 year earthquake forecast for M>5 for S California and published the availability of the Portal to the Earthquake community in the peer reviewed periodical *Computing in Science* *and Engineering*. We document the completion of this objective in the Milestone K *Customer Delivery* write-up at http://quakesim.jpl.nasa.gov/milestones.html.

Project Approach

Interoperability/Portal

Our approach is to build a three-tiered architecture system. The tiers are

1. A portal user interface layer that manages client components.
2. A service tier that provides general services (job submission, file transfer, database access, etc.) that can be deployed to multiple host computers.
3. Backend resource, including databases and earthquake modeling codes.

These tiers are illustrated in Figure 1. The user interacts with the system through the Web Browser interface (top). The web browser connects to the aggregating portal, running on the User Interface Server (**complexity.ucs.indiana.edu** in the testbed). The "Aggregating Portal" is so termed because it collects and manages dynamically generated web pages (in JSP) that may be developed independently of the portal and run on separate servers. The components responsible for managing particular web site connections are known as portlets. The aggregating portal can be used to customize the display, control the arrangement of portlet components, manage user accounts, set access control restrictions, etc. See Figure 2 for an example of the user interface.

The portlet components are responsible for loading and managing web pages that serve as clients to remotely running Web services, shown in the lower figure. Figure 1 shows a DB service running on host 1 (**infogroup.usc.edu** in the testbed), job submission and file management services in the center (typically running on **danube.ucs.indiana.edu** in the testbed) and visualization services (such as RIVA, running on the host **jabba.jpl.nasa.gov**). We use Web Services to describe the remote services and invoke their capabilities. Unless otherwise indicated, solid arrow connections in the figure indicate SOAP over HTTP connections. Broken dash-dot arrows indicate unspecified connections—these are local invocations in our testbed but we are testing ssh/scp connections. We may also use Grid connections (GRAM and GridFTP) to access these applications. Database connections between the Database service and the actual database are handled by JDBC (Java Database Connectivity), a standard technique.

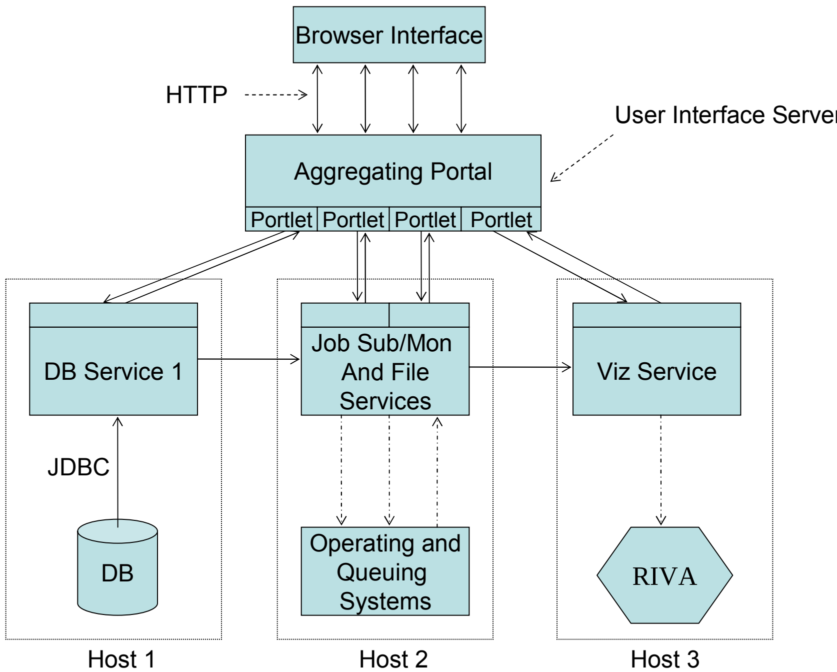

Figure 1 Portal and service architecture.

Figure 2 illustrates the browser interface with portlet-managed components illustrated. The screen shot displays two user interfaces (a visualization of Disloc output on the right, and a the code selection interface on the left). These are independent web pages pulled into the aggregating portal. Tabs across the top can be used to navigate to other portlet component displays.

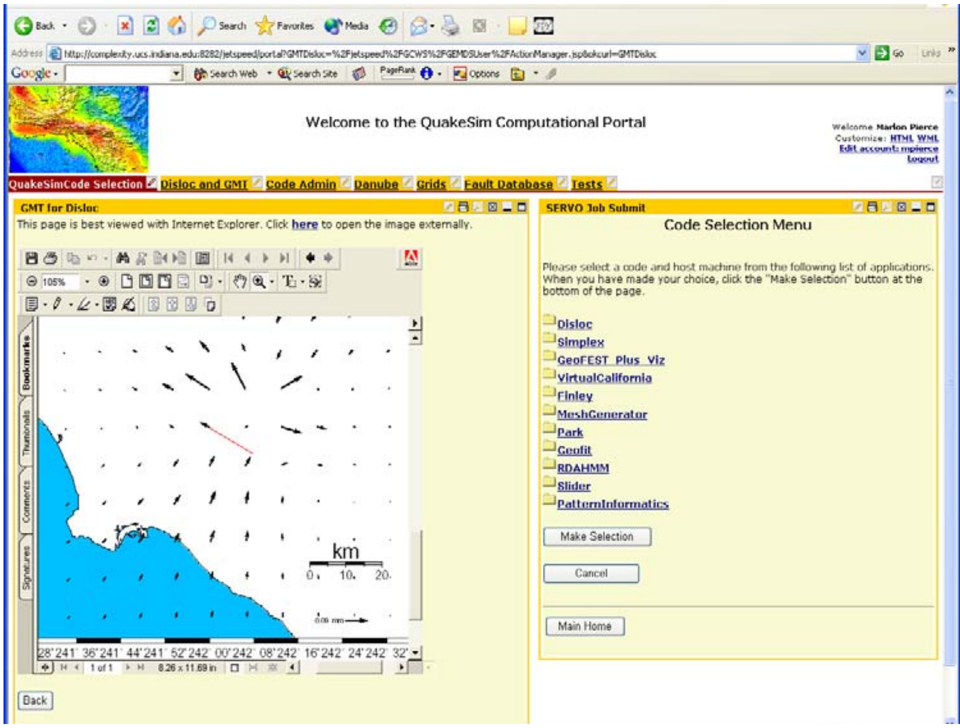

Figure 2 The QuakeSim portal is based on portlet components.

The QuakeSim portal effort has been one of the pioneering efforts in building Computing Portals out of reusable portlet components. Pierce and Fox of the QuakeSim team collaborate with other portal developers following the portlet component approach through the Open Grid Computing Environments Collaboratory (www.ogce.org). This project has been funded by the NSF National Middleware Initiative (Pierce, PI) to develop general software releases for portals and to end the isolation and custom solutions that have plagued earlier portal efforts. Pierce and Fox's involvement with both the QuakeSim project and the OGCE will ensure that the QuakeSim portal will benefit from the larger community of portal development: we may extend the QuakeSim portal to use capabilities developed by other groups and may share the capabilities developed by the QuakeSim portal with the portal-building community.

Fault Database

Solid earth geophysical research is entering an era where cyberinfrastructure tools will be necessary to make effective use of large data sets. We have developed QuakeSim, an earthquake and active deformation processes simulation system, for use by researchers in the seismological, crustal deformation, and tectonic communities. Our primary objective is to develop a virtual laboratory to study earthquake behavior over single or multiple seismic cycles. QuakeSim employs a web browser-based universal Problem Solving Environment (PSE) that utilizes eXtensible Markup Language (XML) schemas to describe the structure of the metadata and to define each datatype. The database component, QuakeTables, provides global real time accessibility to a diverse set of earthquake and fault data, including observations, simulations, and hypotheses. QuakeTables is a semantic based system that provides interoperability for heterogeneous data, different applications and database systems, and user-defined packages.

During the last decade the field of solid earth geophysics has undergone a transformation due to the availability of space-derived crustal deformation data. GPS (Global Positioning System) networks deployed globally are providing precise time-dependent information on how the earth's crust responds to earthquakes and plate tectonic processes. InSAR (Interferometric Synthetic Aperture Radar) data are revealing spatially dense information on how the earth's crust deforms and how faults interact with each other. Deformation of the earth's crust and the interaction between earthquake faults is a complex three-dimensional process. Sophisticated models and the use of high performance computers are required to understand these processes.

The major science goal is to create a virtual laboratory to probe earthquake behavior. The computational goal is to produce a functional system to fully model earthquake-related data. QuakeSim involves building a web browser-based Problem Solving Environment (PSE) that provides a set of links between newly available resources of NASA Earth observing systems, high-performance simulations, automated data mining, and more traditional tools to enable understanding of earthquake and active deformation processes. QuakeSim is the first Web-Services based, interoperable environment for doing large-scale forward models for earthquake processes. Through a Web Services-based portal, it provides global access to geologic reference models of faults and fault data, simple analysis tools, new parallel forward models, and visualization support.

"Cyberinfrastructure tools" for the solid earth sciences will soon become essential for effective utilization of large data sets in the solid earth sciences [http://www.cise.nsf.gov/sci/reports/toc.cfm]. An essential component of QuakeSim is a database system for handling both real and simulated data. The database system is called QuakeTables. QuakeTables was developed for and populated with fault data to provide input for earthquake simulation tools. It will be expanded to include other types of earthquake data. Our web-based universal approach to heterogeneous earthquake databases using QuakeTables is an example of the design, development and implementation challenges in utilizing solid earth science data sets for high performance computing simulations.

Code Improvement

PARK

The main PARK program is a boundary element program that determines the stress on every element of the fault surface due to slip on every other element, using a Greens function approach. The fault constitutive law is used to determine what the slip velocity will be for that stress and this velocity multiplied by the time step gives the slip to be used to calculate the stress in the next time increment. This involves the forward time integration of coupled ordinary differential equations. The integration for previous milestones was done with a fifth order Runge-Kutta[1] scheme with adaptive step size control.

Because the time-steps range over ten orders of magnitude, depending on whether the fault is slipping very slowly in the interseismic period or very fast during an earthquake, the adaptive step-size control is an essential element in the solution.

For this milestone the fifth order Rung-Kutta routine that involved six stages, namely the determination of derivatives six times for every time step, was replaced by a faster second order routine, that involves only two stages and reuses the derivatives calculated at the end of the previous time step to begin the integration at the beginning of the current time step. The adaptive step size scheme is retained. Tests to date show that, as expected, this second order routine is 3 times faster per time step than the fifth order one. The disadvantage is that each time step is smaller, but tests to date suggest that a given model time is reached in essentially the same CPU time as with the fifth order routine. For future users who may want to also try the fifth order routine that uses two copyrighted subroutines from Numerical Recipes, an alternative version of the park.f program is provided that works with those subroutines and contains instructions on how to obtain and modify them to work in this application.

The main program calls a variety of subroutines and the one of these subroutines that calculates the derivatives used in the forward time integration itself calls a Fast Multipole library that is suitable for such Green's functions problems. The Multipole approach allows a number of computations to scale as N log N rather

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[1] Runge-Kutta is a method for forward integration of differential equations that involves calculating derivatives of the functions at the current time and several fractions of potential time-steps in the future, appropriately weighting these derivatives estimating the best derivative value to use and determining the value of the function at the new time by multiplying that best derivative by the appropriate time-step. The fifth-order Runge Kutta method compares estimates made using two different time-steps and, based on this comparison, determines whether a smaller or larger time-step should be used for the next step. This allows for adaptive time-stepping which is extremely important in problems such as this where the time-steps can vary as much as ten orders of magnitude, depending on whether interseismic or a coseismic behavior is involved.

than N^2 as would otherwise be the case. The particular Fast Multipole approach being used allows determination of the degree of grouping of the remote cells based on an analytical approximation to the Greens function. In order to reduce computation time it also renumbers the elements so that those that are near in space are also near in memory.

The main program and most of its subroutines are written in Fortran 90. The Fast Multipole library and its interface program to the main program and its subroutines are written in C. All of these programs run in parallel using MPI.

GeoFEST

The GeoFEST User guide can be found at

http://quakesim.jpl.nasa.gov/GeoFEST_User_Guide.pdf.

In order to demonstrate the value and goals of the final year, including the Milestone G target of a 16 million element case, we first made a substantial effort to generate the largest single-processor mesh that we could for the Landers three-fault earthquake model similar to that used for the Milestone F 1.4 Million element model. Using a standard refinement technique, we generated a 10 Million element mesh. Attempting a somewhat larger mesh resulted in a segmentation fault, likely due to exceeding an index range constraint due to 32-bit arithmetic.

As planned, we pursued a parallel computing solution to generating larger meshes by continuing to integrate GeoFEST with the PYRAMID library. In addition to enabling larger meshes, the method we implemented improves numerical accuracy.

In the first step GeoFEST (on many processors) reads a given, coarse mesh and computes an elastic solution based on prescribed fault slip. This solution is used to compute the strain energy for each element. Elements with excessive strain energy are flagged to indicate areas needing refinement. PYRAMID produces a refined mesh with additional nodes and elements, and produces a suitable partition of these elements among the processors for further computing. The information for each partition re-initializes the finite element data structures for the GeoFEST computations, and the elastic solution and subsequent evolution is computed using this refined mesh. This method was used to generate the Milestone G 16 million element mesh, which produced a high-quality deformation pattern due to the earthquake. (see the Milestone G report at http://quakesim.jpl.nasa.gov/milestones.html).

Virtual California

The approach for Virtual California is to show 10,000 time steps of interaction of 700 fault segments representing the west coast tectonic system.

Scientific Accomplishments

Pattern Informatics Research

With respect to our Pattern Informatics research, we made several significant accomplishments during the period of this project. The first is the update of the scorecard. As of this writing, there have been 18 significant earthquakes in the land area covered by the map. Of these 18 events, 16 of them occurred on, or within the margin of error of, hotspot locations that had been identified in the original paper published on February 19, 2002. The current scorecard is reproduced at: http://quakesim.jpl.nasa.gov/scorecard.html .

In addition, we developed an extension of the basic method that can be summarized as follows:

The steps in the modified method are:

[a] The seismically active region is binned into boxes or pixels of size $.1^o$ x $.1^o$ and all events having $M \geq 3.4$ are used.

[b] Only the top, say, 30% most active boxes are considered.

[c] Seismicity is spatially averaged over each box and its 8-box Moore neighborhood, divided into time steps of 1 day, and the resulting time series is assigned to the central box.

[d] Each time series is normalized in time by subtracting the temporal mean and dividing by the temporal standard deviation.

[e] Each time series is then normalized in space for each value of time by subtracting the spatial mean and dividing by the spatial standard deviation.

[f] If the time at which the data record used begins is t_0, two *intensity maps* $I_1(x, t_b, t_1)$, $I_2(x, t_b, t_2)$ are computed by averaging all the time series from an initial time, t_b to t_1 where $t_0 < t_b$; and then from t_b to t_2. Here t_0 = January 1, 1987. Also, t_1 = November 1, 1993 and t_2 = June 30, 1999 (3 months prior to Chi-Chi mainshock) define the *change interval* from t_1 to t_2. Recall the temporal changes of the Gutenberg-Richter relation in Taiwan (Fig. 3 in Chen, 2003) indicate that major change in seismicity before the Chi-Chi event began in November 1993 and lasted through the mainshock occurrence.

[g] The intensity change $\Delta I(x, t_b, t_1, t_2) = I_2(x, t_b, t_2) - I_1(x, t_b, t_1)$ is computed at each location and the absolute value is taken $|\Delta I(x, t_b, t_1, t_2)|$.

[h] The average of $<|\Delta I(x, t_b, t_1, t_2)|>$ over all values of $t_0 \leq t_b \leq t_{max}$ is then computed. In view of the fact that a time scale $\tau = t_2 - t_1$ has been implicitly chosen, the time t_{max} is chosen to be $t_{max} = t_1 - \tau$. This choice

also gives the averaging time periods in the intervals t_b to t_1 and t_b to t_2 more equal weight, thereby excluding the possibility of large fluctuations (main shocks) occurring just prior to t_1 that may receive too much weight if t_b were integrated from t_0 to t_1.

[i] Finally, the mean squared change in probability $\Delta P(x, t_1, t_2) = \{<|\Delta I(x, t_1, t_2)|>\}^2$ is computed.

[j] Note that steps b), c), f) and g) have been modified from the original algorithm. This modification produces increased stability in the original method by eliminating “noise” that is associated with sites having very low seismicity, and/or location errors of small events.

Using this new modification, we examined the data prior to the 1999 Chi-chi, Taiwan earthquake. The epicenter of the Chi-Chi mainshock was found to exhibit signatures of anomalous activity related to the seismic activation and quiescence in the Taiwan region over a time span of about 6 years before the mainshock. The forecast based on the PI map is clearly different from the map constructed from the Relative Intensity map made using the same data. We also constructed a new 5-year forecast for the California region for the SCEC/RELM group based on this new method (paper referenced above). We conclude that our methods can be applied to areas as diverse as Taiwan and California. Other recent scientific papers include:

JR Holliday, JB Rundle, KF Tiampo and A Donnellan, Systematic procedural and sensitivity analysis of pattern informatics method for forecasting large (M>5) earthquake events in southern California, *PAGEOPH*, in press (2005).

JB Rundle, P B Rundle, A Donnellan , W Klein, D L Turcotte, GC Fox and D McLeod, Variation, correlation and recurrence in topologically realistic, system-level earthquake simulations, Proc. 4th ACES Workshop, Beijing, China (2005).

K.F. Tiampo, J.B. Rundle, W. Klein, Seismicity rate and stress change – stress shadows determined using the Pattern Informatics technique, Proc. 4th ACES Workshop, Beijing, China (2005).

JR Holliday, JB Rundle, KF Tiampo, W Klein, A Donnellan, Modification of the pattern informatics method for forecasting large earthquake events using complex eigenvectors, Tectonophysics, in press (2005).

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K. Z. Nanjo, J. R. Holliday, C-C. Chen, J. B. Rundle, and D. L. Turcotte, Forecasting the location of large future earthquakes in the central Japan and its forecast verification, *Tectonophysics*, in press (2005).

K.Z. Nanjo, J.B. Rundle, J.R.Holliday and D.L. Turcotte, Pattern informatics and its application for forecasting large earthquakes in Japan, *PAGEOPH*, in press (2005).

K.F. Tiampo, J.B. Rundle and W. Klein, Forecasting rupture dimension using the Pattern Informatics technique, *Tectonophysics*, in press (2005).

1906 San Francisco Centennial Earthquake Study

Investigators: Andrea Donnellan, Maggi Glasscoe (Task Manager), Robert Granat, Greg Lyzenga, Charles Norton, Jay Parker

We are proceeding with using QuakeSim tools to study earthquake-related processes, specifically investigating post-seismic deformation following the 1906 Great San Francisco earthquake. This investigation includes continuing development of GeoFEST code, statistical analysis of Virtual California synthetic earthquake data, data mining of deformation results and studying strain wave propagation of viscoelastic response in the 100 years following the event.

We have constructed a simplified, one-fault model of the 1906 earthquake rupture and are investigating the propagation of a strain wave in the region as the viscoelastic lower crust and mantle relax following the coseismic displacement. The San Andreas fault in the preliminary model is 424.57 km long, strikes 148.16°, and is 15 km deep and features three layers: an elastic upper crust, and a viscoelastic lower crust and mantle. Three lower crustal and two mantle relaxation times were tested

GeoFEST code development efforts include creating a user-configurable simulation flow control capability, so that users can flexibly choose how and whether to perform adaptive mesh refinement, elastic and time-stepping solutions, and output generation in all different combinations and parallel mesh-refinement support for problems that include applied surface tractions and buoyancy surfaces. Data mining techniques are being applied to both GeoFEST and VC time series in order to identify anomalous signals that may indicate physics related processes evident in data.

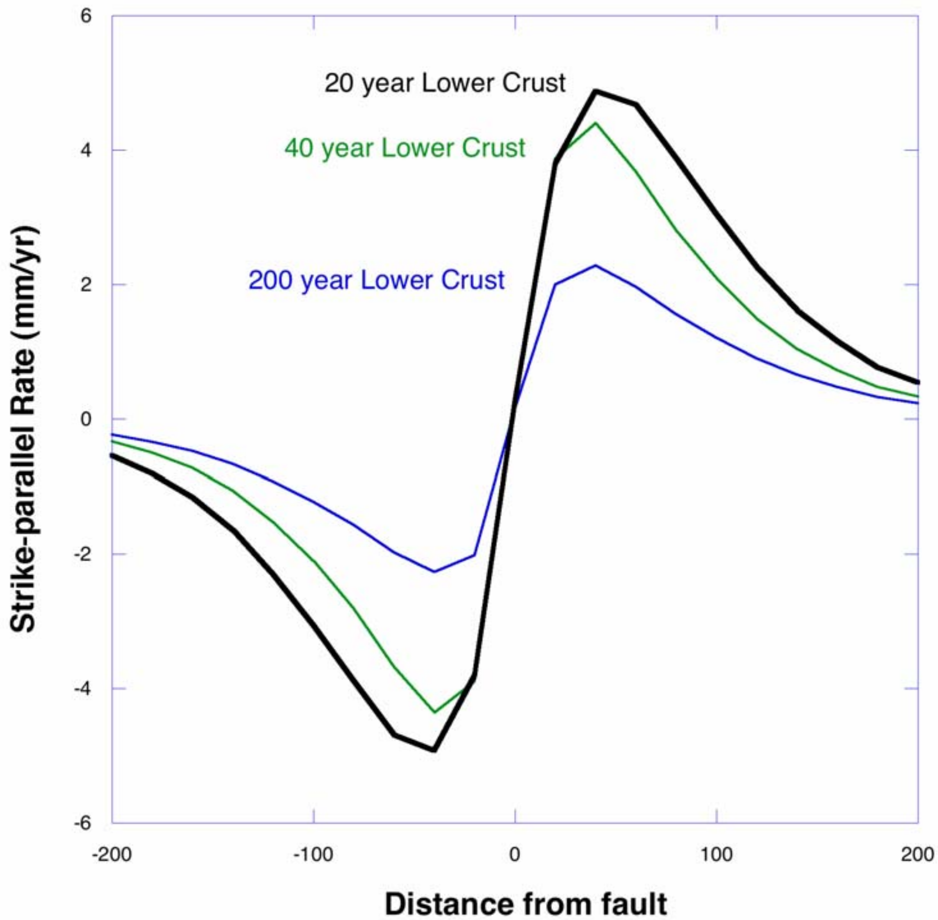

Figure 3. Fault parallel surface velocities for three lower crustal Maxwell times in a slice perpendicular to the San Andreas fault.

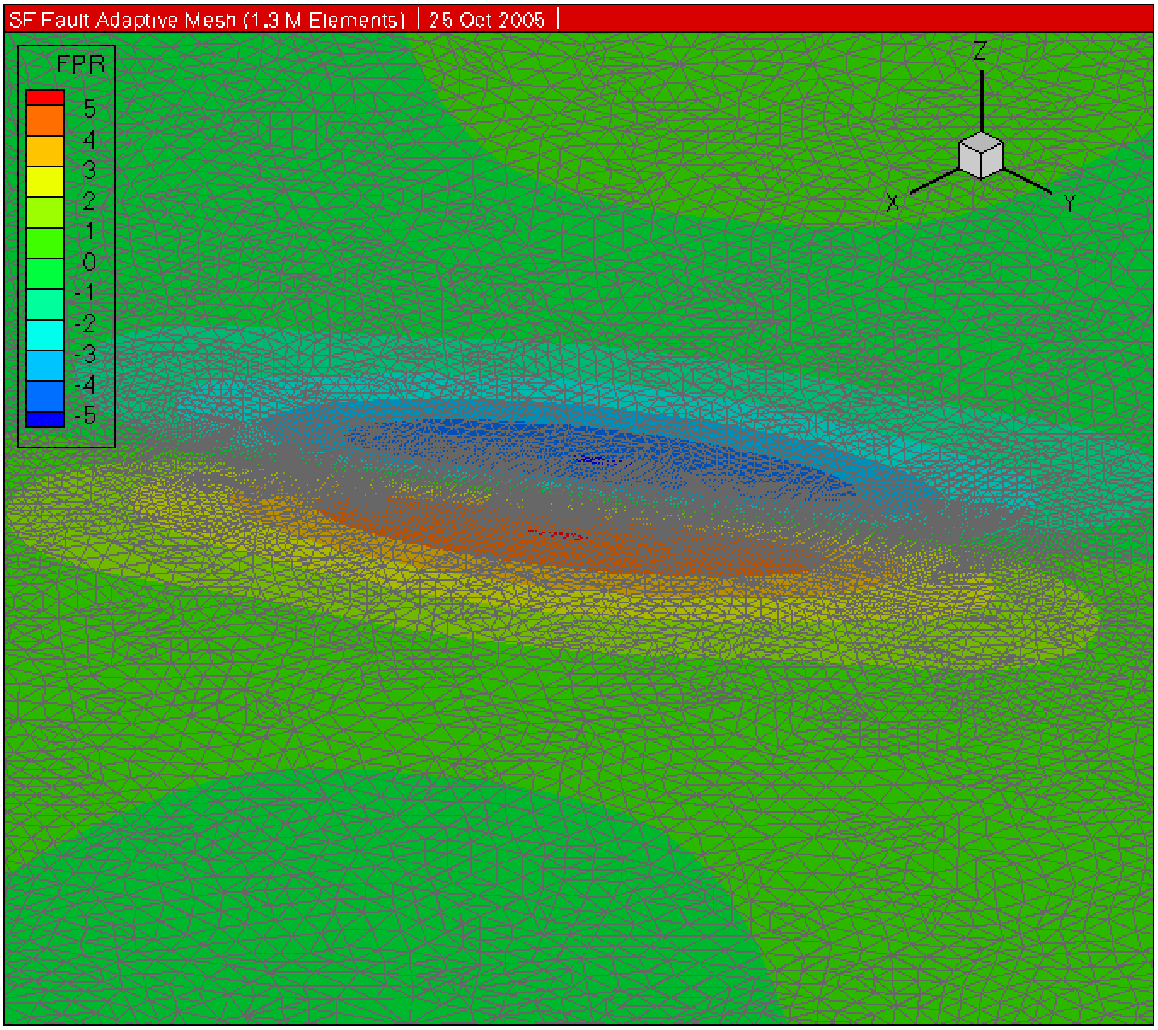

Figure 4. Visualization of the finite element mesh of the San Andreas fault model with fault parallel rates.

Significance of Code Improvements to Geophysics

GeoFEST

High-quality adaptive meshing allows affordable simulation of fine-scale features near the fault in a consistent treatment with smooth, distant features. Both scales are important for modeling the earthquake as a build up of tectonic strain followed by mechanical failure. Both scales are observable by space-based NASA instruments including InSAR and GPS networks. GeoFEST has been demonstrated using adaptive mesh refinement based on an element-wise strain energy metric, which concentrates solution resources in the parts of the domain where high resolution is required. Because approximate solutions determine the final mesh structure, this allows higher accuracy solutions for larger domain sizes and greater faulting complexity for any available computer resource. This is a substantial and necessary step in allowing simulations of surface deformation in active tectonic areas, in that it allows accurate solutions on regional scales (such as Southern California), well beyond the scales of single fault segments used in past studies.

QuakeSim lithospheric modeling with GeoFEST has immediate benefits for the earthquake modeling community, and essential long-term benefits for translating NASA space-based systems into saving lives and property from seismic and volcanic disasters.

Immediate benefits of the ongoing QuakeSim lithospheric deformation modeling program are comparisons of observed and modeled deformation that allow conclusive tests of model components, including fault friction and failure models, subsurface structure, and material characterization. The ability to solve domains with millions of elements implies we can simulate regions with multiple faults, such as the Los Angeles basin. Interactions among slipping faults and possible emergent structures from these nonlinear interactions is in the research forefront for improving earthquake risk forecasts. Many kinds of simulation codes are beginning to be employed for this new kind of work across the earthquake community, but an adaptive-mesh-based finite element code has close to the greatest degree of flexibility in including the effects of realistic structures in the Earth in a heterogeneous domain. QuakeSim's GeoFEST has unique value in validating these other simulations and determining when other multiple-fault models are leaving out too many material effects.

Proposed missions such as InSAR and GRACE follow-on will produce enormous amounts of data, and this data can be effectively used for understanding the earth system and its catastrophic hazards only when linked to a multiscale modeling environment. The GeoFEST finite element code is well suited to become a component of a comprehensive risk assessment system and earth system model for optimal data assimilation from space-based deformation and gravitational observations. The goal is an integrated system of precision surface deformation monitoring, combined with a modeling system that incorporates processes at multiple scales. This will create a new forecasting capability for the timing and scope of solid earth hazards, comparable to those now in place for El Nino events and hurricanes.

PARK

The development of the PARK code has paved the way for realistic detailed modeling of a wide range of earthquake sizes, starting with modeling now underway for earthquakes at Parkfield, CA. The geometry of the mesh for these models is being built so that it is able to accurate portray the complexity of the actual geometry of the hypocenter locations of observed microseismicity at Parkfield as well as the M6 earthquakes that occur in this segment of the San Andreas fault. The model will be used to develop an understanding of in what situations small earthquakes grow into larger ones and in what situations they do not. Since all earthquake begin at one spot and grow to their eventual size, developing an understanding of what conditions are need to the grown to large damaging earthquakes is an important part of the scientific effort to understand the predictability of earthquakes. Research is now underway using the PARK code on NSF sponsored research into the pattern in time and space of seismicity at Parkfield, CA, though a grant from the Southern California Earthquake Center.

Vital California

Our code improvements with Virtual California have allowed us to run simulations of earthquake events lasting millions of years. Using these computations, we have been able to conclusively show that the appropriate statistical distributions that describe interacting earthquake faults are most commonly the Weibull distribution. Until now, the Working Group on California Earthquake Probabilities have used both the log-normal and the Brown passage time distributions for their forecasts of future events. In addition, we have also been able to show that the Parkfield sequence of events is also best represented by Weibull statistics.

These results are summarized in the papers:

> P. B. Rundle, D. L. Turcotte, J. B. Rundle, and G. Yakovlev, Recurrence times for Parkfield earthquakes: Actual and simulated, *Bull. Seism. Soc. Am.*, in review (2005)

> P.B. Rundle, J.B. Rundle, K.F. Tiampo, A. Donnellan and D.L. Turcotte, Virtual California: Fault model, frictional parameters, applications, *PAGEOPH*, in press (2005).

Technology Accomplishments

Interoperability/Portal

We completed the following accomplishments during the final year of development:

- Added all of the milestone codes: developed user interfaces, made use of available services (particularly context management, file transfer, and Apache Ant services for job management)
- Added multiple user support (the prototype portal only supported a single user account)
- Wrapped GMT (General Map Tool) and IDL (Interactive Data Language) services for visualization

- Built specific Web Service applications for Simplex, Disloc, PI (GMT) and GeoFEST (IDL)
- Developed GPS and Seismic catalog databases and services, integrating them into the portal, and integrating them with RDAHMM
- Developed ssh wrappers to remotely execute file transfers and command execution through the portal
- Improved packaging of the portal using Apache Ant for compiling and deploying
- Developed testing framework using HTTPUnit
- Completed code administration tools and code management user interfaces and services

Database Middleware

Four categories of database functions performed by the middleware were implemented before the final year of the project: insertion, selection, deletion, and modification. This middleware is portable since JAVA-based web technologies are cross-platform. There are three divisions of customized browser-based user interfaces that have been implemented: Fault Database, Layer Database, and California Geological Survey Database.

In addition to the browser-based user interfaces, customized web-service stubs are implemented by using the Web Service Description Language (WSDL) interface and the JAVA programming language. These stubs are used to retrieve data from different databases to perform further operations (e.g, simulations).

Code Improvement

GeoFEST

GeoFEST simulates stress evolution, fault slip and plastic/elastic processes in realistic materials. The products of such simulations are synthetic observable time-dependent surface deformation on scales from days to decades. Scientific applications of the code include the modeling of static and transient co- and post-seismic Earth deformation, Earth response to glacial, atmospheric and hydrological loading, and other scenarios involving the bulk deformation of geologic media.

GeoFEST has been demonstrated using adaptive mesh refinement based on an element-wise strain energy metric, which concentrates solution resources in the parts of the domain where high resolution is required. Because approximate solutions determine the final mesh structure, this allows higher accuracy solutions for larger domain sizes and greater faulting complexity for any available computer resource. This is a substantial and necessary step in allowing simulations of surface deformation in active tectonic areas, in that it allows accurate solutions on regional scales (such as Southern California), well beyond the scales of single fault segments used in past studies.

For Milestone G, elastic and viscoelastic deformation is simulated for 16 million finite elements, for a duration of 1000 time steps. The significant increase is in the number of elements, which was about 55,000 for the baseline case and 1.4 million elements for the Milestone F code improvement (both of which also run 1000 time steps). Note that the baseline case was modeled on the 1994 Northridge earthquake, using a single fault of 300 square km in a domain of 240 x 240 x 100 km. The Milestone F demonstration case is based on the 1992 Landers event, using three closely arranged faults within an 865 square km area in a domain volume area of 1000 x 1000 x 60 km.] The Milestone G demonstration is still based on the 1992 Landers event – but now has higher mesh density near the faults, and 200 km depth, to reduce boundary effects for the viscoelastic relaxation.

Code	Machine Wallclock Time	Processors	Date	Elements	Time Steps
GeoFEST Milestone **E**	Solaris workstation (JPL) 13.7 Hours	1	July 30, 2002	55,369	1,000
GeoFEST Milestone **F**	*Thunderhead* (GSFC) 2.8 Hours	64	September 1, 2003	1,400,198	1,000
GeoFEST Milestone **G**	*Cosmos* (JPL) 12.0 Hours (under 13.7 allowable)	490 (well under 880 allowable)	March 26, 2005	16,021,034	1,000

Table 1: Computer runs demonstrating baseline, Milestone F performance enhancements and Milestone G performance enhancements for GeoFEST.

- GeoFEST correctly generates millions of elements and computes stress-displacement solutions with message-passing (MPI) code on hundreds of processors. This has been verified for 65 million elements.
- Heuristic mesher on desktop can vary density with high generality: High near fault edges, very low to extend to far boundaries. This produces a good starting point for adaptive refinement.
- The PYRAMID library has been integrated with GeoFEST, and is used for partition management and the generation of quality refined meshes.
- Strain energy refinement converges to correct elastic solution based on an earthquake slip event.
- Validation with known solutions indicates 1-2 iterations is sufficient to arrive at an acceptable solution. An iteration means: find strain energy based on an initial solution, refine mesh, compute improved solution.

We attained an 83% scaled efficiency demonstrated by the Milestone G 16 million element simulation on 490 processors, compared to a 4 processor run with similar element count per processor. This demonstrates very low parallel overhead for computing, so long as at least tens of thousands of elements reside on each processor.

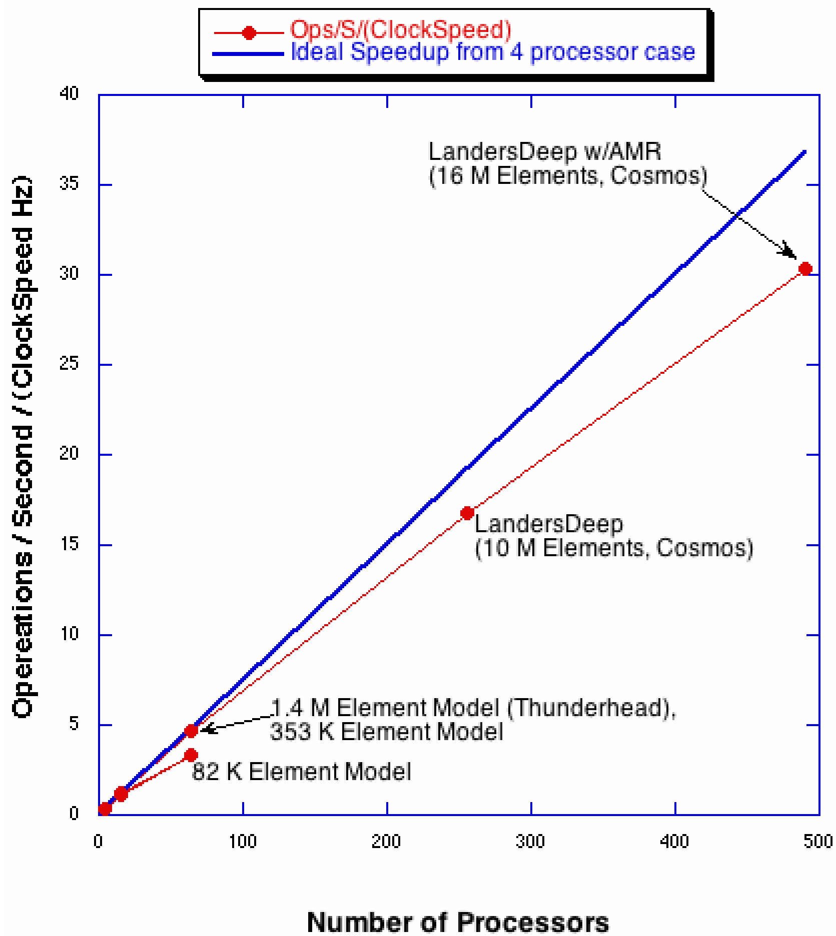

Figure 5: GeoFEST: Scaling of work (on linear scales) in GeoFEST time-step function with number of processors on three sizes of problems (on *Thunderhead* cluster computer, GSFC) plus two very large problems (on *Cosmos* cluster computer, NASA JPL). Blue indicates ideal scaling (from 4 processors). Expressing work in operations/wallclock time scaled by processor speed allows comparison of sizes (and platforms) in a single plot.

PARK

The PARK code is designed to help: *compute the history of slip, slip velocity, and stress on a vertical strike-slip fault that results from using state-of-the-art rate and state frictional constitutive laws on the fault for a specific geographic setting at Parkfield, California.*

The boundary conditions are those appropriate for Parkfield and the distribution of constitutive properties on the fault zone are as realistic as our ability to characterize the subsurface properties of the fault there allow. The methods developed in solving this problem can be generalized to other geologic settings in which the fault geometry, the boundary conditions are not so simple and multiple faults are involved.

The grid used in Milestone G has 400,000 elements. The primarily change from the 150,000 element model used for Milestone F was a large increase in the number of square elements that are 7.4 meters on an edge, there being 273,375 of these in the current model and only 5040 in the previous model. The increase in the number of these fine elements was made in the area of the model where the earthquake is expected to nucleate. Some minor adjustments in the number of some of the larger elements were made to result in the change from 150,000 to 400,000 elements.

The PARK code implementation is the first simulation of an earthquake fault using the fast multipole technique, using a library originally developed for astrophysical, gravitationally-interacting bodies.

Code	Machine Wallclock Time	Processors	Date	Elements	Time Steps
PARK Milestone **E**	*Chapman (AMES)* 7.888 Hours	1	September 18, 2002	15,000	500
PARK Milestone **F**	*Chapman* (AMES) 7.879 Hours	256	August 15, 2003	150,000	5,000
PARK Milestone **G**	*Dell Linux Cluster (JPL)* 34.518 Hours*	512	May 27, 2005	400,000	50,000

Table 2: Computer runs demonstrating baseline, Milestone F performance enhancements and Milestone G performance enhancements for PARK. Note that Milestone G wallclock time beat the allowable time of 39.440 hours (five times the baseline run) and this was accomplished with fewer processors than specified in the milestone.

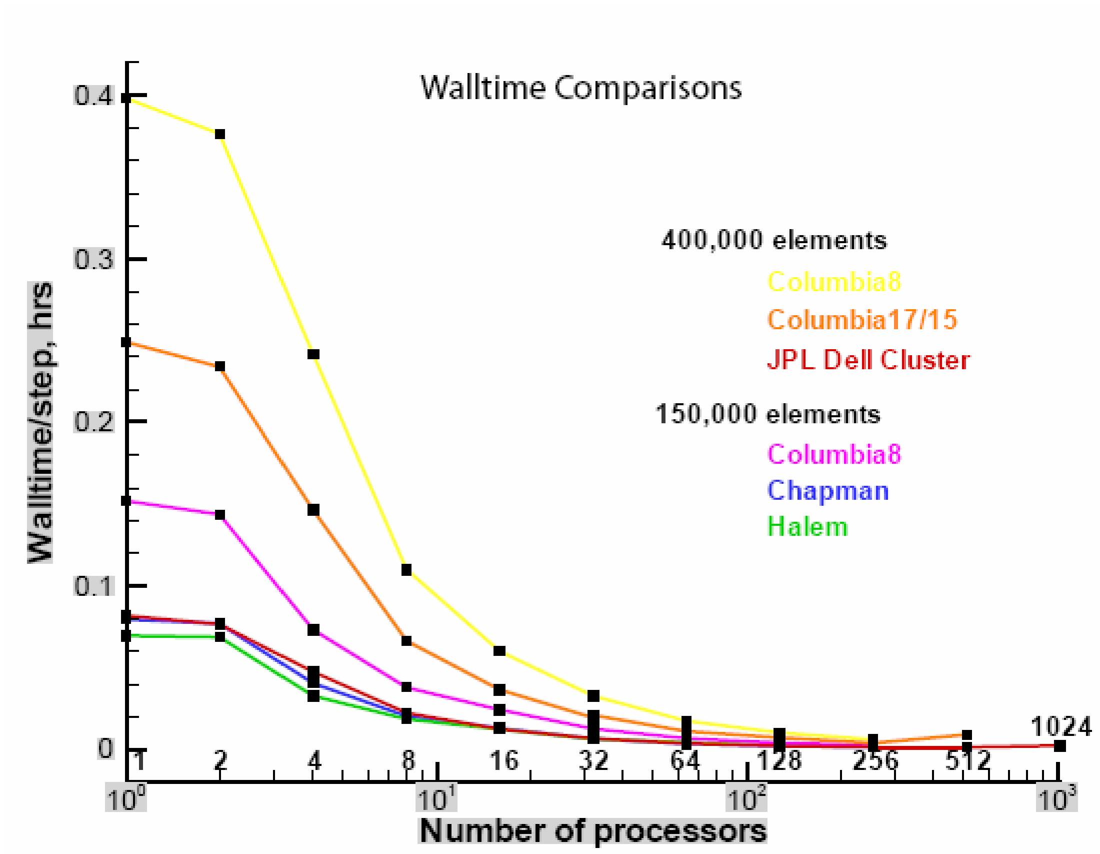

Figure 6 PARK Walltimes.

Virtual California

We were tasked with achieving a speedup of the VC simulation code of better than M/2, where M is the number of processors, on a machine having at least 256 processors. The machine was used was the Ames Lomax cluster with Turing front end.

We ran the code for 10,000 time steps and 700 fault elements (700^2 = 490,000 Green's functions). The version of code that we ran was optimized to produce multiple earthquake histories for use in computing statistics on earthquake occurrence (specifically a magnitude-frequency relation) and for eventual use in data assimilation and ensemble forecasting. Each of the code implementations on each processor generated a different earthquake history because each used different random number seeds. The number of earthquakes we compute thus scales as M, the number of processors. In evaluating performance of speedup, and since the number of events computed increases with the number M of processors, we define a "unit of computed work" as a computed earthquake having a magnitude $M \geq 5$. Thus we measured the speedup relative to the work done, so we need to define the "performance time" $\equiv P_T(M)$ of a run on M processors as the net CPU time divided by the number of M ≥ 5 earthquakes. Thus:

$P_T(M) \equiv$ (CPU-net on M) / Work $\equiv$ (CPU-net on M) / (# of M ≥ 5 events)

We then computed the speedup S(M) as:

$S(M) \equiv P_T(1) / P_T(M)$

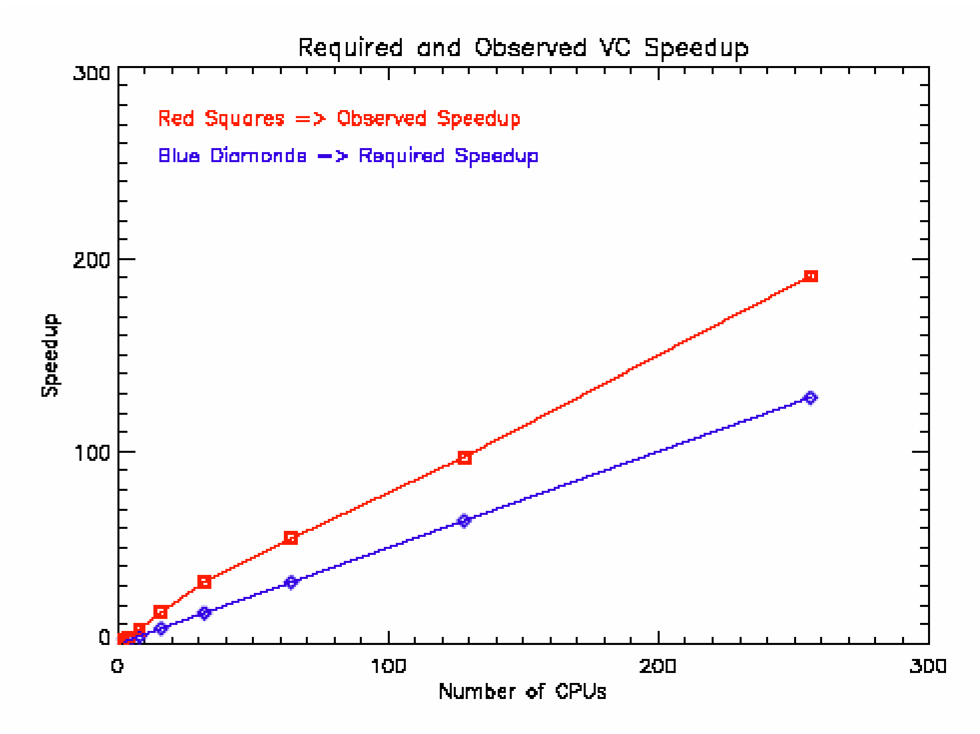

Figure 7. Virtual California speedup vs. number of CPUs.

QuakeSim Plans/Status

QuakeSim work is continuing through NASA's AIST project. We also have acquired time on the Columbia computer at NASA Ames to use the high performance software developed through QuakeSim. We will be pursuing additional funds through NASA's Decision Support CAN and future AIST calls. Unfortunately, there is not currently a program for development of high performance computational codes, however we will continue software development where possible and will apply for sources of funding to continue high performance code development as they become available. In the meantime, we will continue working with collaborators, will disseminate QuakeSim software, will participate in workshops, and will promote the use of QuakeSim in the larger geoscience community.

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New Technology Reports

NTR 30543 – *GeoFEST*
Performs finite element simulation of tectonic stress and strain in two and three dimensional domains, for elastic, viscoelastic and faulted materials.

NTR 40469 – *Fault Database*
Provides a web-interface and database management system for earthquake faults and related information for constructing simulations.

NTR 40472 – *General Earthquake Model (GEM) Portal*
Provides a web-based environment to geophysical databases, applications codes and visualization. Allows user customization of interface and workflow.

NTR 40581 – *Parallel GeoFEST*
Performs finite element simulation of tectonic stress and strain in two and

three dimensional domains for elastic, viscoelastic and faulted materials. Uses the Pyramid library to enable parallel mesh partitioning and simulations. Parallel conjugate gradient solver ensures scalability for efficient solution on very large systems.

NTR 41077 – *Discloc*
Calculates Earth surface displacements for an elastic dislocation (earthquake fault) in an isotropic elastic half space.

NTR 41078 – *Simplex*
Calculates fault displacements from Earth surface deformation data. Inverts suface geodetic data for fault location in an isotropic elastic half space.

NTR 41079 – *QuakeSim*
Models interacting earthquake fault systems from the fault nucleation to tectonic scales.

Publications – Complete List for Entire QuakeSim Project

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Donnellan, A. Taped TV interviews on KNBC, KTLA, KABC, and Fox affiliate on earthquake forecasting using pattern recognition and the use of InSAR for studying earthquakes, October 2004.

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Donnellan, A. Live interview with Los Angeles based radio station, KFWB, on recent earthquakes and InSAR, September 2003.

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Donnellan, A. Taped interview for Los Angeles based radio station, KFWB, QuakeSim, InSAR, and Earthquakes, January 2004; segments aired through April 2004.

Donnellan, A. Live interview with Los Angeles based radio station, KFWB, on InSAR and computing, December 2003.

Donnellan, A., Rundle, J.: NASA Earth Science Update, Washington D.C., December 2003

Donnellan, A. Live interviews on QuakeSim Computational Technologies project, including CNN Headline News and top story feature on Next@CNN, May 2003.

Donnellan, A. Filmed to be featured in an exhibit on earthquakes, New York's Natural History Museum, April 2003.

Rundle, J. 2005 interview by Rene Bransby from Australia, who wants to do a video program: (Rene Bransby, Researcher - Becker Entertainment, Level 1, 11 Waltham St, Artarmon NSW 2064AUSTRALIA, T: +61 (0) 2 9425 1122) .

Rundle, J. 2005 interview with producer Matha Moon of National Geographic, who hopes to do a 2006 special on earthquakes.

Rundle, J. 2005 interviews with Orange County Register, San Jose Mercury News, Sacramento Bee, National Geographic, SF Chronicle, local ABC, CBS, NBC TV; Interviews on CNN, MSNBC.

Selected Talks and Briefings

Space Technology and Solid Earth Science Briefings – Andrea Donnellan

- House Science Committee, April 2004.
- Jason Rothenberg, OMB examiner for NASA Code Y, February 2004.
- Chip Groat, Director of the US Geological Survey, January 2003.
- Michele Burkett, Staff Assistant, House Committee on Appropriations, January 2003.
- Congressman Dreier, February 2003;
- Congressman Rhorabacher, February 2003;
- Mike O'Brien and Joe Wood, NASA HQ, Code I, August 2003.
- Amy Kaminski, OMB examiner for NASA Code S, August 2003.
- Margaret Leinen, NSF Deputy Director for Geosciences, October 2003
- Congressional Committee on Science Research, November 2003.
- John Marburger, President's science advisor, December 2003.
- Lecture on the use of space technology for studying earthquakes as part of the 40th anniversary of planetary exploration, California State Capital, Sacramento, August 2002.
- NASA Associate Administrator Ghassem Asrar on solid earth computational technology needs, May 2002.

Other Briefings – John Rundle

- CEPEC review, John Parrish, California State Geologist, Sept 20, 2005.

Outreach – Andrea Donnellan

- Living on a Restless Planet, Using Space Technology to Study Earthquakes:
  - AIAA Chapter, Lancaster, California, September 2005
  - Mojave Region High School 4.0 Dinner talk, April 2005
  - Kern Antelope Historical Society, Rosamond, California, April 2005

  - Patuxent River Navy Test Pilot School, March 2005
  - IEEE Aerospace Conference Plenary Speaker, Big Sky, Montana, March 2005
  - Navy League, Bakersfield, February 2005
  - Minerological Society of Southern California, December 2004
  - NASA Summer High School Apprenticeship Research Program, June 2004.
- Von Karman Public Lecture, JPL and Pasadena City College, January 2003.
- Adventurer's Club, Los Angeles Chapter, April 2003.
- Career Talk, Norma Coombs Alternative School First Grade, December 2004.
- Talked to Girl Scout master trainer about Donnellan's work and work at JPL, October 2004.
- Our Restless Planet, 2004 Caltech Alumni College, June 2004.
- Understanding Earthquakes from Space, Beverly Hills Forum, June 2004.
- Using Space Technology to Understand Earthquakes and Land Surface Processes, K-5th grade French/American School Lycee International de Los Angeles (LILA), Monrovia Campus, March 2004.
- Understanding Earthquakes from Space, Stanford Professional Women of Los Angeles, January 2004
- Talk on earthquakes and space technology to 3–5 graders at St. Elizabeth's School in Altadena, California, April 2003.
- Talk on *Plate Tectonics and You: A Cool View of Earthquakes*, Happy Valley School, Summer Science Program to high school students, July 2003.
- *Using Space Technology to Understand Earthquakes*, IEEE Women in Engineering, Ventura Chapter, October 2003.

Other Presentations

Donnellan, A. Living on a Restless Planet, Earth Science Research and Applications: Geodetic Infrastructure as Enabling Technology, Talk on Behalf of Ghassem Asrar, NASA HQ, International GPS Service 10th anniversary symposium, Bern, Switzerland, March 2004.

Donnellan, A., The US QuakeSim Program: Modeling Earthquakes on High-Performance Computers, International Workshop on Geodynamics: Observation, Modeling, and Computer Simulation, Tokyo, Japan, October 2004.

Donnellan, A. Advances in US earthquake simulation and modeling, Fourth ACES Workshop, Beijing, China, July 2004.

Donnellan, A., The US QuakeSim and SERVO Projects, The Third International Conference on Continental Earthquakes, invited keynote talk, Beijing, China, July 2004.

Donnellan, A., G. Fox, J. Rundle, T. Tullis, D. McLeod, L. Grant, Numerical Simulations for Active Tectonic Processes: Increasing Interoperability and Performance, Summary Symposium on the Solid Earth Simulator Project, Tokyo, Japan, Invited, 2003.

Donnellan, A., R. Granat, J. Rundle, Detecting Features in Seismic and Geodetic Data, 35th Symposium on the Interface: Computing Science and Statistics, Salt Lake City, Invited, 2003.

Donnellan, A., G. Fox, J. Rundle, D. McLeod, T. Tullis, L. Grant, J. Parker, M. Pierce, G. Lyzenga, A. Chen, J. Lou, The Solid Earth Research Virtual Observatory: A web-based system for modeling multi-scale earthquake processes, 2002 Fall AGU Meeting, San Francisco, Invited, 2002.

Donnellan, A., NASA Perspective on Earthquake Research, US/Japan Panel on Natural Hazards Research, Morioka, Japan, November 2002.

Donnellan, A., Computational Technologies Project Update at the Computational Technologies Project science team meetings, July 2002, January 2003.

Fox, Geoffrey. Applications as Web (Grid) Services and Related Issues Argonne National Laboratory November 10 2003.

Fox, Geoffrey, and David Walker e-Science Technology/Middleware (Grid, Cyberinfrastructure) Gap Analysis and OMII SEAG Meeting DTI June 20 2003

Fox, Geoffrey. iSERVOGrid Architecture Working Group Third ACES Working Group Meeting Brisbane June 5 2003.

Fox, Geoffrey and Marlon Pierce Grid Technology Implications for ACES and SERVOGrid Third ACES Working Group Meeting Brisbane June 5 2003

Fox, Geoffrey Some Future Semantic Grid Activities CrisisGrid and ServoGrid presentation at GGF7 Tokyo Semantic Grid Meeting March 6 2003.

Fox, G., D. Gannon, M. Pierce, M. Thomas Overview of Grid Computing Environments presentation at GGF7 Tokyo Portal Architecture Workshop March 6 2003 summarizing document of same name

Pierce, A. Metadata and the Semantic Web Access Grid Presentation for PET August 29 2003.

Pierce, Marlon, Choonhan Youn, and Geoffrey Fox Interacting Data Services for Distributed Earthquake Modeling ICCS Melbourne Australia June 4 2003

Academic Training

***Fall 2003, 2004, 2005 CSUN Geology 464** (Applied Geophysics) course: Professor Gerald Simila and his geophysics students used the QUAKESIM portal to run DISLOC to model the 1994 Northridge earthquake. Dr. Simila had a NASA Faculty Fellowship Program (Summer 2003) at JPL with Dr. Andrea Donnellan. His project involved using the QUAKESIM portal to test the usability and development of the fault modeling programs (DISLOC and SIMPLEX) and associated graphics.

STUDENTS and POSTDOCS

Jordan Van Allsburg – University of California, Davis, Graduate Student, Department of Physics, graduate student working on percolation analysis foundations for statistical earthquake data analysis.

Galip Aydin – Indiana University, graduate student developing the GML schemas to describe seismicity and GPS data. Implemented services for extracting legacy data from online repositories. Building services and user interfaces to extract sections of the data.

Teresa Baker – Massachusetts Institute of Technology, BS undergraduate student, used Simplex, Disloc, and GeoFEST to model deformation associated with the Northridge earthquake and adjacent Ventura basin prior to matriculation in May 2003. Teresa is currently working on the QuakeSim project at JPL.

Anne Yun-An Chen – University of Southern California, PhD candidate is undertaking development of the fault and federated databases. She is also a a member of the Semantic Information Representation Group. She received her M.S. degree in Computer Science from the University of Southern California. Her current research focuses on federated database systems, web services, and information recommender systems.

James Holiday – University of California, Davis, Graduate Student, Department of Physics, developing and testing new Pattern Informatics methodologies.

Shan Gao – University of Southern California, PhD graduate student is developing the interoperability aspects of the fault databases.

Maggi Glasscoe – University of California, Davis, MS graduate student used geoFEST to model observed GPS deformation and coupling between the crust and the mantle in the Los Angeles basin prior to matriculation in December 2003. Maggi has taken a full-time position at JPL and currently supports the QuakeSim project at JPL.

Miryha Gould – University of California, Irvine, PhD graduate student helped devleop the geological aspects of the fault database.

Dr. Gleb Morein – University of California, Davis, Postdoctoral Fellow developing parallel slider code for high performance applications. He is also converting Virtual California to parallel/high performance format.

Paul Rundle – Undergraduate Student, U.C. Davis, working on earthquake fault model data bases and static data assimilation for Virtual California.

Ahmet Sayar – Indiana University, graduate student who worked on developing authoring tools to create scripts for coupling services needed by the QuakeSim portal. This exploratory work was determined to be less suitable for the portal than the subsequently developed HPSearch algorithms.

Dr. Robert Shcherbakov – University of California, Davis, Postdoctoral Fellow Analysis of seismicity and geodetic databases for Pattern Informatics earthquake forecasting.

Sang Soo Sung – University of Southern California, PhD graduate student assisted in the development of the federated databases and manages the QuakeTables database.

Dr. Choonhan Youn - currently works on the GEON project. Youn defended his Ph.D. thesis in Nov 2003 at Syracuse University. Dissertation work was based in part on work performed as part of the NASA CT QuakeSim project.

Letters of Support

The following letters of support for the QuakeSim work are attached:

- Dr. Ned Field: Research Geophysicist, United States Geological Survey
- Dr. Nick Beeler, Earthquake Hazards Team, United States Geological Survey
- Dr. Gerry Simila, Director – Center for Earthquake Studies, California State University, Northridge
- Dave Manaker, Graduate Student Researcher, University of California, Davis

United States Department of the Interior

U.S. GEOLOGICAL SURVEY

525 S. Wilson Ave
Pasadena, CA 91106

October 6, 2005

Dr. Andrea Donnellan

Jet Propulsion Laboratory

800 Oak Grove Dr., MS 238-600

Pasadena, CA 91109-8099

Dear Andrea:

This letter is to express my support for continued development of Virtual California and other QuakeSim elements.

As you know, I am a Research Geophysicist at the United States Geological Survey, and I serve on the planning committee and am the seismic-hazard-analysis focus-group leader of the Southern California Earthquake Center.

Perhaps most relevant to your program, I am leading an ongoing Working Group on California Earthquake Probabilities (WGCEP), the results of which will be used to set earthquake insurance rates throughout California. Virtually all previous WGCEPs have made assumptions regarding the statistics of earthquake recurrence intervals. However, there are not enough observations to support or refute these previous assumptions. Therefore, I have recently made extensive use of Virtual California to test some plausible models. The synthetic data provided by Virtual California have proven to be very valuable in this regard.

Previous WGCEPs have only been next-event forecasts, whereas proper hazard analysis needs to forecast all possible sequence of events over the lifetime of a building. Given significant earthquake triggering and stress interactions demonstrated by numerous recent studies, the only rational way to forecast all possible sequence of events will be using Virtual-California types earthquake simulators (via model steering and data assimilation techniques).

Currently QuakeSim is the only multi-disciplinary effort focused on developing such a model. This is very unfortunate given the importance of the problem and the fact that no one knows exactly how to solve it (making multiple efforts appropriate). There is a long way to go before such models can be used in official forecast, but the QuakeSim program is clearly in the lead with respect to the Virtual California earthquake simulator.

In the mean time, and as I stated above, the results of Virtual California are also proving very useful in terms of constraining the statistical models being applied in ongoing, more traditional forecasts.

Sincerely,

Dr. Edward (Ned) H Field
Research Geophysicist
United States Geological Survey

Jet Propulsion Laboratory, Earth and Space Sciences Division
Mail Stop 183-335, 4800 Oak Grove Drive
Pasadena, CA 91109-8099

10/03/05

I have closely followed research and development of NASA QuakeSim project overseen by Andrea Donnellan and Michele Judd of JPL. This project has produced a number of needed technical advances in computational geophysics, in particular parallel finite element (GEOFEST) and boundary element (PARK) computer codes for earthquake and deformation modeling.

My research, largely funded by the National Earthquake Hazard Reduction Program consists of making laboratory observations of faulting, developing contact asperity-scale physics models of the lab observations and applying the models to understand geodetic observations of natural faulting and accompanying seismicity. Modeling requires computer programs capable of large scale and long duration simulations.

For the past 6 months I have been using components of the parallel Fast Multipole Method (PARK) developed by QuakeSim to model earthquake nucleation in plane strain and true 2D. This approach will be extended to whole cycle earthquake models with a wide range of magnitude in a collaborative study with Terry Tullis, one of the QuakeSim Co-PI's. Separate research on nucleation both in large (2 meter) laboratory experiments and earth-scale model faults with heterogeneous properties will be pursued concurrently.

In addition to these scientific applications of the Quakesim technology, I plan to complete a technical paper and error analysis of the approximations used in the numerical technique that underlies the multipole method. Boundary element methods are widely used in models of stress transfer and earthquake triggering, I expect widespread, long term interest and use of this component of the Quakesim development by many international researchers. Similar approximation schemes as used in multipole method may be applied to finite element methods such as GEOFEST, expanding the possible spatial scope and duration of future earthquake and deformation simulations. This is a topic for subsequent research.

Future advances in understanding the physics of earthquakes require that the necessary funding is available to maintain the Quakesim programs to keep pace with advances in parallel architecture and operating systems. I also strongly encourage further funding to extend the Quakesim technologies and develop new and improved computational approaches building on the Quakesim advances.

Sincerely,

N. M. Beeler, United States Geological Survey, Earthquake Hazards Team
345 Middlefield Rd., MS 977, Menlo Park, California 94025

California State University
Northridge

Department of Geological Sciences
College of Science and Mathematics

October 24, 2005

Dr. Andrea Donnellan
Deputy Manager, Earth and Space Sciences Division
Mail Stop 183-335
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109-8099

Dear Andrea:

During the summers of 2003 and 2004, I participated in the NASA Faculty Fellowship Program at JPL in your division. My project involved using the QuakeSim portal to test the usability and development of the fault modeling programs (Disloc and Simplex) and associated graphics to model the observed GPS measurements from California earthquakes, including the 1994 Northridge, 1999 Hector Mine, and 2003 San Simeon. This unique research experience then allowed me to incorporate the QuakeSim project into my Geology 464 (Applied Geophysics) course in Fall 2003 and 2004 so that the geophysics students could model the 1994 Northridge earthquake. In addition, my senior student modeled the 2004 Parkfield earthquake for his senior thesis research project. We also presented a poster entitled, "Analysis of aftershocks and modeling of GPS displacements from the December 22, 2003 San Simeon and September 28, 2004 Parkfield, California earthquakes", at the Geological Society of America meeting in San Jose, California in May 2005. Presently, I have a new graduate student who will continue the research on the Parkfield earthquake, and we will again use of the QuakeSim this Fall in Geology 464. Thank you very much for supporting my summer fellowships and providing the CSUN students with access to a very valuable research project.

Sincerely,

Gerry Simila

Gerry Simila
Professor, Geophysics

18111 Nordhoff Street · Northridge · California 91330-8266 · (818) 677-3541 · fax (818) 677-2820 · e-mail *geology@csun.edu*

The California State University · Bakersfield · Channel Islands · Chico · Dominguez Hills · Fresno · Fullerton · Hayward · Humboldt · Long Beach · Los Angeles · Maritime Academy · Monterey Bay · Northridge · Pomona · Sacramento · San Bernardino · San Diego · San Francisco · San Jose · San Luis Obispo · San Marcos · Sonoma · Stanislaus

UNIVERSITY OF CALIFORNIA, DAVIS

September 30, 2005

Andrea Donnellan, Ph.D.
Deputy Manager, Earth and Space Sciences Division
Mail Stop 183-335
NASA Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109-8099, USA

Subject: GeoFEST v. 4.5

Dear Andrea:

I would like to take the opportunity to thank the QuakeSim staff, in particular Greg Lyzenga, Ken Hurst, and Margaret Glasscoe, for assisting me with implementing GeoFEST here at UCDavis. They have provided the guidance and support necessary for me to complete my doctoral research. I am currently using GeoFEST v. 4.5 to compute solutions for use with continuum damage mechanics as applied to lithospheric deformation. My research currently only utilizes the simplest of GeoFEST's capabilities to calculate elastostatic solutions. However, in the future I plan on using GeoFEST's capabilities to handle layered models, viscoelasticity, and faulting. I am also looking forward to using the QuakeSim portal and the adaptive mesh refinement.

I am hopeful that, in the future, improved documentation and training classes will become available to assist me and other scientists in using GeoFEST.

Sincerely,

David M. Manaker
Graduate Student Researcher
Department of Geology – University of California, Davis